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RESEARCH ARTICLE

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Optimization of cable layout designs for large offshore wind farms

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Summary

Installation of a wind farm exposes several problems such as site selection, placement of wind turbines in the site, and designing of cable infrastructure within the farm. The latter problem, called cable layout design, is the determination of cable connections among turbines and one or more transmitters such that energies generated by turbines will be sent through the cable routes, and eventually gathered at the transmitter(s). This problem is especially important for offshore wind farms where the featured and expensive cables are used. The main objective of the present study is to address the cable layout design problem of offshore wind farms to reduce cable costs in the design using optimization-based approaches. The problem, firstly, is modelled as a mixed integer linear program (MIP) under a set of real-life constraints such as different cable and transmitter types and non-crossing connections between the turbines. Then, a novel mathematical model, which is a modification of the MIP model by imposing several heuristic rules, is proposed to solve the layout problem of large offshore wind farms. Experiments on a set of small- and moderate-sized test instances reveal that the heuristic model, MIP_H, reduces the computer time nearly 55% compared to that of MIP model while the average cable costs generated by the models are close to each other. MIP_H, besides its efficiency, provides more cost-effective layouts compared to MIP model for large-sized real-life examples. Additionally, a comparative study on MIP_H and existing methods in the literature shows that MIP_H is able to solve all instances of the real-life examples providing less cable costs in average.

KEYWORDS

cable layout, cable routing, integer programming, wind farm optimization

1 | INTRODUCTION

Renewable energy is one of the major energy resources for countries in terms of continuity and sustainability in energy production. Wind power, among the renewable energy resources, has been growing to become a key element in electricity generation. The World Wind Energy Association declared that 53 900 MW new wind power capacity was added in 2018 and the worldwide wind capacity reached 600 GW by the end of 2018 which corresponds to more than 5% of the world's electricity demand. As wind energy provides affordable green energy, investors look for lower installation and operating costs to design cost-effective wind farms. There occur several important problems in the design of a wind farm such as the selection of a right site to construct a wind farm,[1-3] layout of turbines in the farm,[4-9] installation of electrical infrastructure[10-13] and connection of turbines and transmitters in the farm through electrical cables. Connection of turbines and transmitters using different cable types to send all the energy production towards one or more transmitters is known as cable layout problem. This problem is an important optimization problem in the design of wind farms since capacities and lengths of cables affect both total investment cost and power losses. Cable layout problem also has been mentioned with different names such as cable routing problem,[13] array cable layout problem,[10,12] and infrastructure planning[14] in the literature. Network of cable connections must be at least a minimum spanning tree. Additionally, the amount of energy sent through each cable cannot exceed capacity of the cable. This constraint makes cable layout problem NP-hard as the minimum spanning tree problem with capacitated arcs is NP-hard.[14] Therefore, cable layout design is also important in the operational research community.

Although both onshore and offshore wind farms include similar design problems, installation costs in the offshore farms are significantly higher than that of onshore. Readyhough[15] stated that the cost of cables and cable installation accounts for nearly 27% of an offshore wind farm capital cost. Blanco[16] also indicated the possibility of decreasing the total installation cost of a wind farm up to 10% by designing a good cable layout. Lumbreras and Ramos[17] presented a comprehensive review of design problems in offshore wind farms including the electrical layout problem. They showed that even though a pre-established layout such as radial, ring, and star topologies simplifies the problem, it is not true optimization. Furthermore, these topologies are insufficient to provide reliable cable layouts. Larsen et al[18] introduced an integrated framework, called TOPFARM, as an optimization tool where the design problems of wind farms are handled sequentially. Wedzik et al[19] also proposed an integrated approach to turbine-transmitter location and cable connection problem to minimize total investment and operation costs including the energy losses for the entire wind farm. On the other hand, most of the studies address the cable layout problem assuming a number of turbines and transmitters were already installed due to the difficulty of the problem. Existing studies in the literature propose optimization models and methods, or heuristic methods to solve the cable layout design problem while several studies benefit from both optimization and heuristic approaches.

Lingling et al[20] focused on location and connection scheme of transmitters where wind turbines installed in arrays. They applied genetic algorithm (GA) to find the cable connections between transmitter pairs and also cable layout among turbines. Smail et al[21] proposed a combination of GA with a problem-specific constructive algorithm in which similar design issues in Lingling et al[20] are considered. They considered the locations of transmitters and assignments of wind turbines to the transmitters using GA. Then, a set of wind turbines and one transmitter within the same group were connected one-by-one considering the shortest Euclidean distances and feasibility conditions. In the study of Smail et al,[21] the objective was to minimize total installation cost which consists of cable, equipment, and transmitter costs. In addition to these cost items, Jenkins et al[22] also included minimization of power losses in the design of cable layouts for offshore wind farms. They developed a greedy algorithm which is based on the connection of nearest turbines. Once a layout was constructed by the greedy algorithm then GA is applied to improve this layout. Gonzalez-Longatt et al[23] treated the cable layout problem of offshore wind farms as a multiple travelling salesman problem (TSP) where each transmitter corresponds to a salesman and a group of turbines corresponds to the cities visited on a ring. Gonzalez-Longatt et al[23] minimized a modified cost function of transmitters, substations and cables using GA under the constraints of multiple TSP. Pillai et al[24] used both heuristic algorithms and mixed-integer linear programming to find locations of transmitters including cable connection decisions for an offshore wind farm. In the study of Pillai et al,[24] firstly, turbines were clustered to obtain transmitter positions and then cable paths within the clusters were determined. The mixed-integer linear programming model was used to solve capacitated minimum spanning tree problem taking the input parameters from the cable paths obtained before. Zhao et al[25] aimed to solve the problem to find the positions of transmitters and converters, the number of the cable types, and the best connection topology of the wind turbines using GA. Dahmani et al[26] also used GA to minimize the total cost of identical cable types where the locations of multiple transmitters were known. As a result, the literature survey on the heuristic methods proposed for the cable layout problem shows that most of the studies decompose the multi-transmitter wind farms into sub-problems where each sub-problem includes a single transmitter and a group of turbines assigned to this transmitter. Then, the sub-problems are solved using GA, in general, besides several problem-specific heuristics. Therefore, it can be concluded that connection of turbines to a single transmitter still is a core problem in the cable layout design.

Since the cable layout problem is a long-term design problem, computer time which is necessary for execution of a proposed method is relatively less important compared to the total cost of the obtained solution. That is why in the literature there are numerous studies such as[10,11,13,17,27-29] which focus on optimization models in purpose of having cost-effective layouts. Hou et al[29] proposed a dynamic minimum spanning tree algorithm to solve the offshore wind farm cable layout problem under the power loss condition. Cerveira et al[11] solved the problem by using integer linear programming and considering capacitated minimum spanning trees with several cable types and power losses. Also, they addressed the optimal cable connection among the turbines and the transmitter where both power losses and cable costs are minimized. Berzan et al[27] focused on cable layout problem where single and multiple cable types are used separately. In the single cable type case, they proposed a minimum cost flow problem to assign turbines to transmitters, then the Esau-Williams heuristic was used to arrange the connection between the turbines and transmitters. They proposed a mixed-integer programming model to determine connections of multiple cable types and amount of flow through the cable connections. Hertz et al[28] modelled the cable layout problem of onshore wind farms as a mixed integer program (MIP) considering two different types of cables and allowing parallel cables which are installed into the same dug hole in the ground. Bauer and Lysgaard[10] developed an open vehicle routing approach to solve cable connection problem of two real-world offshore wind farms using a hop-indexed integer programming formulation. Fischetti and Pisinger[13] focused on the layout of cables of several types considering both the cases of power losses exist or do not exist. They included non-crossing cable constraint into a MIP to prevent cable damages and costly installation of crossing cables and also, a maximum number of cables connected to the transmitter due to the type of transmitter was involved as a constraint in the proposed program. Fischetti and Pisinger[13] solved the proposed MIP both exactly and heuristically. The heuristic solution method they proposed, called matheuristic, is a hybridization of exact solution method and heuristic rules. They suggested four different heuristic rules which are based on the fixing of some cable connection variables to reduce the feasible solution space. They conducted experiments on a testbed of real-world cases and showed that the matheuristics are able to find cost-effective cable layouts. Fischetti and Pisinger[30] also solved the same cable connection problem in Fischetti and Pisinger[13] using mixed integer models. Banzo and Ramos[31] developed a MIP to determine the cable layout by including system efficiency, investment costs, and system reliability for a real offshore wind farm. Another MIP to model the cable layout of an offshore wind farm was introduced by Lumbreras and Ramos.[32] They applied the Benders' decomposition technique to solve the layout problem of large-sized wind farms. Consequently, the optimization methods developed to deal with the cable layout problem are generally based on the mixed integer programming models assuming a single transmitter due to the difficulty of the problem. On the other hand, it is not possible to compare the superiority of one model to another one since they involve different realistic constraints and/or objectives in the design of cable layouts.

In this paper, a MIP is proposed to solve cable layout problem of offshore wind farms under the constraints of different cable types in varying capacities, different transmitter types, and non-crossing cables where the locations of turbines and a single transmitter are given in advance. MIP model is based on the flow conservation constraints. However, it is also enhanced by adding several new constraints which impose certain features in a feasible cable layout. Additionally, a new mathematical model is presented by modifying MIP model including several heuristically derived constraints to be able to find lower cost solutions for large-sized wind farms. Even the modified MIP, called MIP_H, cannot guarantee the optimality, the experimental studies show that this model can find optimal layouts for small wind farms and generates cost-effective layouts for larger wind farms. MIP and MIP_H models are also tested on sample instances of the layout problem in which double transmitters exist to analyse applicability of the models to multi-transmitter case. It is observed that both MIP and MIP_H can be applied to the case while majority of the optimization approaches in the literature decompose the multi-transmitter case into single-transmitter problems. Furthermore, a new repair algorithm is presented to eliminate crossing cables in the layouts obtained by the suggested models. Only Fischetti and Pisinger,[13,30] dealt with the same design issues considered in the present study. Especially, the non-cross cable constraint is rarely considered in the existing literature. The studies which involve this constraint necessitate a data preprocessing. On the other hand, it is experimentally shown that the repair algorithm presented in this study is very fast to find non-cross layouts. In conclusion, the main contribution of this paper is to provide high qualified solutions to the cable layout problem, especially for large-sized wind farms, avoiding from the cross cables under several realistic constraints. As offshore wind farms require high investment cost due to difficulties in the installation, any improvement in the investment cost will be quite significant. Accordingly, we also intend to contribute to the literature since there is room for improvement of the cable layouts of offshore wind farms when the mentioned constraints are taken into account.

2 | PROBLEM DEFINITION AND PROPOSED MIP MODELS

The cable layout problem can be defined on a graph $G = (V, A)$ where V is the set of identical turbines and a single transmitter while A is the set of connections between each pair of turbines and transmitter in V. Figure 1 is an illustration of the problem on an instance with eight turbines and one transmitter. It is assumed that positions of turbines and transmitter have been already identified on a grid design of the site where the site is represented as an $N \times N'$ matrix. Therefore, location of a turbine v can be defined by the pair (i, j) where $i \in N$ and $j \in N'$. Installation of a cable of type t, $t \in T$, with capacity Cap_t between turbines at positions (i, j) and (k, l) incurs a cost of Cost_t. The objective is to minimize the total of Cost_t while providing transmission of power generated by each wind turbine to a single transmitter. Therefore, all the wind turbines and transmitter must be connected through a cable in a feasible layout. As an important engineering constraint, the power is unsplittable through the cable layout.[28] This means that the generated power by a single turbine including the transferred power via this turbine must exit from the turbine using a single cable. Because of the unsplittable property of power, each turbine can be regarded as a resource of one power unit. Hence, cable capacities can be stated as the maximum number of turbines which the cable can carry. As an additional constraint which depends on the type of transmitter, the number of cables connected to the transmitter is limited by a given maximum cable number, C.

Parameters of the problem which are known in advance are listed below:

$$x_{ij} = \begin{cases} 1, \text{there exists a turbine in location } (i,j) \\ 0, \text{otherwise} \end{cases}$$

$$x_{R,R'} = \begin{cases} 1, \text{there exists a transmitter in location } (R,R') \\ 0, \text{otherwise} \end{cases}$$

TN: Total number of turbines in the wind farm.

D_{ijkl}: Euclidian distance between turbines in locations (i, j) and $(k, l.)$.

Cap_t: Capacity of cable of type t in terms of number of turbines.

Cost_t: Cost of cable of type t per distance unit.

C: Maximum number of cables which can be connected to the transmitter.

Finally, decision variables of the problem are defined as:

$$w_{ijkl}^{t} = \begin{cases} 1, \text{if turbines } (i,j) \text{ and } (k,l) \text{ are connected with a cable type } t \in T, i,k \in N, j,l \in N' \\ 0, \text{otherwise} \end{cases}$$

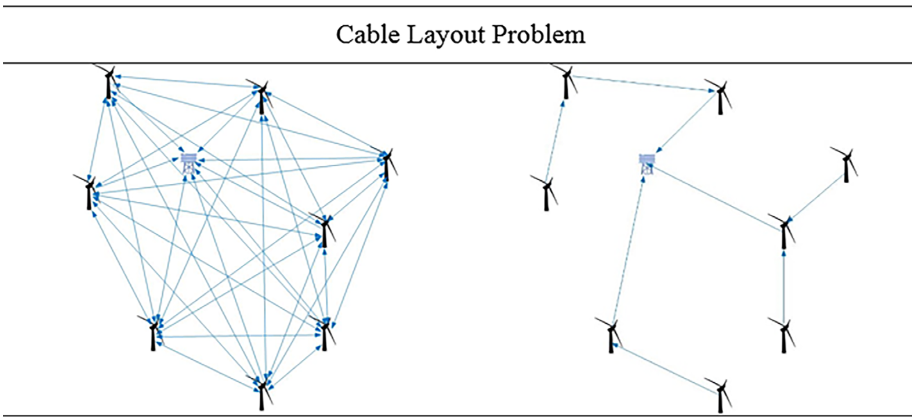

FIGURE 1 An illustration of cable connections [Colour figure can be viewed at wileyonlinelibrary.com]

flow_{ijkl} = Total flow from turbine in (i,j) to turbine in (k,l).

2.1 | Proposed mixed integer programming model

MIP model developed in this study to capture the cable layout problem is given by Equations (1) to (15). The objective function minimizes the total cost of cables in the layout. Conservation of flow at each turbine is guaranteed in Equation (2). In Equation (3), total flow into the transmitter is assured to be equal to the total turbine numbers. Equation (4) provides that there is a single cable leaving a turbine. Equation (5) stipulates installing at most one cable between any pair of turbines whereas Equation (6) defines the unidirectionality of cables. Amount of flow between pairs of turbines which are connected by a cable of type t is limited by the capacity of cable type as stated in Equation (7). Total number of cables connected to the transmitter is restricted by C as shown in Equation (8). The equations from Equation (2) to Equation (8) are basic constraints which must be used to model the cable layout problem as an integer program. One can solve small- or moderate-sized instances of the problem to optimize Equation (1) imposing the binary requirement of decisional variables w^t_{ijkl} in Equation (14). In this study, the solution space of the problem defined by Equations (2) to (8) is further restricted by imposing additional constraints given by Equations (9) to (13) to provide a better formulation of the cable layout problem which is more convenient in solving larger sized instances. Obviously, a feasible solution to the cable layout problem must be at least a spanning tree in which there exists a single path between every pair of nodes (turbines plus transmitter). Therefore, the total number of cables connected the turbines and a transmitter must be at least equal $|V| - 1$ where $|V| = \text{TN} + 1$ as provided by Equation (9). Equations (10) and (11) avoid having overlapping cables in each row of N and in each column of N', respectively. Equation (12) means that the connection of two turbines located in the same row is impossible if there is another turbine in the same row which is installed between these two turbines. Similarly, the connection of two turbines in the same column is prevented if there is another turbine located in the same column and between the two turbines as defined by Equation (13). Finally, binary requirements and non-negativity of the variables are stated by Equations (14) and (15).

$$\min \sum_{(i,j),(k,l)\in A} \sum_{t\in T} \text{cost}_t w^t_{ijkl} D_{ijkl}, \tag{1}$$

$$\sum_{k=1}^{N}\sum_{l=1}^{N'} \text{flow}_{ijkl} - \sum_{k=1}^{N}\sum_{l=1}^{N'} \text{flow}_{klij} = 1 \;\forall (i,j)\in V, i\neq R, j\neq R', \tag{2}$$

$$\sum_{k=1}^{N}\sum_{l=1}^{N'} \text{flow}_{k,l,R,R'} = \text{TN}, \tag{3}$$

$$\sum_{k=1}^{N}\sum_{l=1}^{N'}\sum_{t=1}^{T} w^t_{ijkl} = 1 \;\forall (i,j)\in V, i\neq R, j\neq R', \tag{4}$$

$$\sum_{t=1}^{T} w^t_{ijkl} \leq 1 \;\forall (i,j)\in V \;\forall (k,l)\in V, \tag{5}$$

$$w^t_{ijkl} + w^t_{klij} \leq 1 \;\forall t\in T \;\forall (i,j)\in V,\; \forall (k,l)\in V, \tag{6}$$

$$\text{flow}_{ijkl} \leq \sum_{t=1}^{T} \text{Cap}_t \times w^t_{ijkl} \;\forall (i,j)\in V,\; \forall (k,l)\in V, \tag{7}$$

$$\sum_{i=1}^{N}\sum_{j=1}^{N'}\left(\sum_{t=1}^{T} w^t_{i,j,R,R'}\right) \leq C, \tag{8}$$

$$\sum_{(i,j),(k,l)\in A}\sum_{t=1}^{T} w^t_{ijkl} \geq \text{TN}, \tag{9}$$

$$\sum_{l=1,l\neq j}^{N'}\sum_{t=1}^{T} w^t_{ijil} \leq x_{ij} \;\forall (i,j)\in V, \tag{10}$$

$$\sum_{k=1,k\neq i}^{N}\sum_{t=1}^{T} w^t_{ijkj} \leq x_{ij} \;\forall (i,j)\in V, \tag{11}$$

$$w^t_{ijil} \leq 1 - x_{is} \;\forall (i,j)\in V,\; \forall (i,l)\in V, t\in T,\; \forall s, s>j, s<l, \tag{12}$$

$$w^t_{ijkj} \leq 1 - x_{sj} \;\forall (i,j)\in V,\; \forall (k,j)\in \text{V}, t\in T,\; \forall s, s>i, s<k, \tag{13}$$

$$w^t_{ijkl} \in \{0,1\} \;\forall (i,j)\in V,\; \forall (k,l)\in V, t\in T, \tag{14}$$

$$\text{flow}_{ijkl} \geq 0 \;\forall (i,j)\in V,\; \forall (k,l)\in V. \tag{15}$$

2.2 | Heuristically enhanced mixed integer programming model

The pre-experiments on the MIP model were conducted using the branch-and-bound solver of LINGO (linear-integer-nonlinear-global optimization) software in a limited time (10 hours). These experiments showed that the gap between the lower bound and the best solution both generated by the MIP varies between 5% and 10% depending on the instance characteristics, especially, number of turbines and turbine locations. Although run time is not a main criterion for such a long-term design problem, we could not improve the solutions obtained from the MIP model for large-sized instances even the time limit is allowed to be very long. Therefore, MIP model was modified by introducing additional constraints which are derived heuristically to obtain lower cost cable layouts especially for the instances which cannot be solved using MIP. The modified model, called MIP_H, cannot guarantee to find global optimal solutions because of the heuristically derived constraints. However, these constraints significantly reduce the size of the solution space and hence enable to find a good feasible solution within the same or less computer time. The heuristic constraints in MIP_H are explained as below:

Proposition 1 If there exists a cable t between turbines in locations *(*i, j*)* and *(*k, l*)* then there must be at least one unit of flow between these turbines. It is assumed that $\frac{\sum_{t=1}^{T}\frac{\text{cost}_t}{\text{Cap}_t}}{T}$ is the estimated cost of sending one unit of flow between any pair of turbines where T is the number of available cable types. Therefore, right-hand-side of the inequality given in *(16)* is the total estimated cost of flows which are sent through cable lengths and it can be used as a lower bound on the total cost of cables*:*

$$\sum_{(i,j),(k,l)\in A}\sum_{t\in T}\text{cost}_t w^t{}_{ijkl}D_{ijkl}\geq\frac{\sum_{t=1}^{T}\frac{\text{cost}_t}{\text{Cap}_t}}{T}\sum_{(i,j),(k,l)\in A}\text{flow}_{ijkl}D_{ijkl}. \tag{16}$$

Proposition 2 There exist several types of cable $t \in T$. Assume that the cable types are ordered according to their capacities such that $Cap_1 < Cap_2 < \cdots < Cap_T$. Since there is a single cable which leaves a turbine, the type of entering cables into the turbine depends on the type of leaving cable. That is, total capacities of inflow cables of a turbine should not be larger than the capacity of its outflow cable as given by the following inequality*:*

$$\sum_{r>t}^{T} w^r{}_{psij} \leq 1 - w^t{}_{ijkl}\ \forall (i,j),(k,l),(p,s)\in V, t=1,\ldots,T-1. \tag{17}$$

Proposition 3 In a grid design of site, each turbine is assumed to be pre-installed in a location *(*i, j*)*. As the number of cables both entering and leaving a turbine in *(*i, j*)* increases, the possibility of having cross-cables increases. Our pre-experiments showed that the total number of cables connected to a turbine should be at most four. Therefore, a maximum of four cables connected a turbine is stipulated as follows*:*

$$\sum_{k=1}^{N}\sum_{l=1}^{N'}\sum_{t=1}^{T}\left(w^t_{ijkl}+w^t_{klij}\right)\leq 4\ \forall (i,j)\in V, i\neq R, j\neq R'. \tag{18}$$

Proposition 4 Proposition *3* makes each turbine having at most four turbines which can be connected. Even there exist $\binom{\text{TN}-1}{4}$ number of possible connections for each turbine, except the transmitter, the nearest neighbour turbines are more favourable to connect. We have determined the fourth nearest neighbour, NN_v, for each turbine $v \in (i, j)$ by a simple data processing. Then*,* a parameter, named radius distance *(*RD*)*, has been determined as $\text{RD} = \alpha \max_{v\in V}\{\text{NN}_v\}$ where α *1* is a constant. Therefore*,* RD becomes the maximum allowed distance to install cable between two turbines. The pre-experiments in this study show that α = *1.1* is good enough to prevent the following constraint to be very tight. Here*,* M is assumed to be a sufficiently big positive constant*:*

$$M\left(1-w^t{}_{ijkl}\right)\geq D_{ijkl}-\text{RD}\ \forall (i,j),(k,l)\in V,(i,j)\neq(R,R'),(k,l)\neq(R,R'),\ \forall t\in T. \tag{19}$$

2.3 | Dealing with the crossing cables

Although the constraints given by Equations (10) to (13) are introduced to cope with the crossing cables in the same row or column of the wind farm site, it is still possible to have crossing cables which connect the turbines or transmitter in different rows or columns. Therefore, a repair routine was developed to eliminate crossing cables, if they exist in the optimal solution found by MIP or MIP_H. The pseudo-code given in Figure 2 describes how the proposed routine works. MIP or MIP_H model

FIGURE 2 A pseudo-code of the proposed repair routine to eliminate crossing cables

For a given instance of cable layout problem, select the integer programming model (MIP or MIP_H)
Repeat
1. Run the integer programming model to find cable layout solution W^*
2. Let c is the set of crossing cable pairs $\left(w_{ijkl}^{z,t}, w_{prsu}^{z,t}\right)$, $z \in c$ in W^*
3. Let f is the set of turbines (i, j) which appears in c
4. Fix the variables in W^* which do not result in crossing cables: $w_{ijkl}^{t} = 1,\ \forall t \in T, \forall (i, j) \notin f, \forall (k, l) \notin f$
5. Eliminate at least one variable which result in crossing cables: $\left(w_{ijkl}^{z,t} + w_{prsu}^{z,t}\right) \leq 1,\ z \in c$

Until $c = \emptyset$

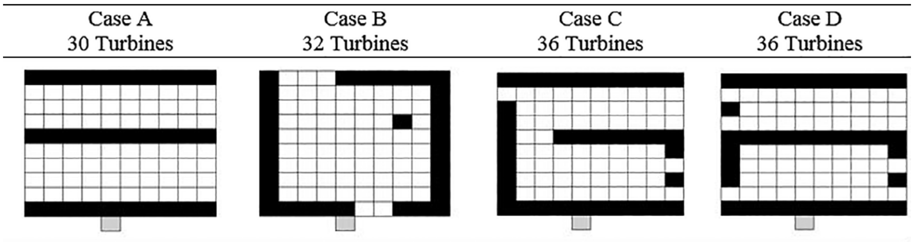

FIGURE 3 Optimal turbine positions[33]

is called to solve a given instance. If solution W^* found by the model contains crossing cables, they are determined in step2 by examining the solution and set c is formed by pairs of the variables which cause cross cables. In step3, turbine locations associated with the crossing cables are included in another set f. Then, variables in the initial solution W^* which do not create any crossing cables are fixed in the model as in step4. Step5 shows the additional constraints included into the model to eliminate at least one of the binary decision variables $\left(w_{ijkl}^{t}, w_{prsu}^{\acute{t}}\right)$ which result in crossing of the cable of type t between the turbines (i, j) and (k, l) and type $\acute{t}$ between turbines (p, r) and (s, u). Whenever a new constraint or constraints are added to the integer model, the model is re-executed and the repair procedure is repeated until there is no crossing cable pair in the solution W^* .

3 | DESCRIPTION OF TEST INSTANCES AND REAL-WORLD CASES

Performance of the presented models, firstly, is tested on a set of test instances and then on a set of real-world cases. The computational results are given Section 4, while both the test and real-world cases are explained in the following subsections.

3.1 | Test instances

To obtain an instance of cable layout problem addressed in this study following data is necessary:

1. Locations of turbines and transmitter(s), and hence Euclidean distances between each pair of turbines and transmitter.
2. Cable types in terms of capacity and cost per unit length.
3. Cable connection limit to the transmitter.

We utilized the reported results in the literature to obtain the data given above. For (1), the turbine layouts reported by Ulku and Alabas-Uslu[33] are used. Ulku and Alabas-Uslu[33] solved the turbine layout problem to minimize the total cost of turbine investment per unit of total power production considering the following wind regimes which are also widely used in the literature of turbine layout problem.

Case A: one wind direction from north to south with a constant wind speed of 12 m/s.

Case B: eight wind directions with equal probabilities of occurrence with a constant wind speed of 12 m/s.

Case C: 36 wind directions with equal probabilities of occurrence with a constant wind speed of 12 m/s.

Case D: 36 wind directions with unequal probabilities and variable wind speed of 8, 12, and 17 m/s.

Figure 3 shows the layouts reported in Ulku and Alabas-Uslu[33] under the four different wind regimes. The turbine layout problem studied by the researchers does not involve the optimal location of the transmitter because the transmitter has not an impact on the total power generated. In this study, we added a single transmitter as represented by grey colours in the layouts given in Figure 3. Transmitters should be close to the shore in an offshore wind farm. Thus, we selected the position of

TABLE 1 Test instances of the cable layout problem

Instance No.	Layout	No. of turbines	*C* (maximum cable number connecting transmitter)	Used cable set
Test1	Case A	30	10	CableSet1
Test2			4	CableSet8
Test3			4	CableSet9
Test4	Case B	32	10	CableSet1
Test5			4	CableSet8
Test6			4	CableSet9
Test7	Case C	36	10	CableSet1
Test8			4	CableSet8
Test9			4	CableSet9
Test10	Case D	36	10	CableSet1
Test11			4	CableSet8
Test12			4	CableSet9

the transmitter assuming the last row of the layouts is closest to the shore. Finally, test instances are described in Table 1. In the third column of Table 1, the number of turbines in the wind farm reported in Reference 33 is given. The last two columns of the table show the cable connection limit to transmitter and cable sets, respectively. The cable sets in different cost and capacities are selected from Table 2 as provided by Fischetti and Pisinger.[13] Thus, 12 instances were obtained considering different cable sets and the cable connection limits for each layout of the four wind regimes (from A to D).

3.2 | Real-world instances

Fischetti and Pisinger[13] used combinations of different cable costs and cable capacities for five real wind farms, which are currently in operation, to analyse the performance of their solving methods. Columns 2 to 5 of Table 2 describe these wind farms giving the owner country, turbine types installed, the total number of turbines, and maximum cable connections to a single transmitter, while columns 6 to 8 gives combinations of cable capacities and cable costs studied by Fischetti and Pisinger.[13] In the last column, cable set names are used to mark the resulting 13 different combinations of cable costs and capacities.

4 | COMPUTATIONAL RESULTS

Performance of the proposed integer programming models, MIP and MIP_H, were comparatively tested firstly on the test instances and then on the real-world cases described in Section 3 where LINGO software package was used as a solver. The runs were executed on a 4.20 GHz Intel Core i7 computer with 32 GB of RAM. The results obtained by using MIP_H on the real case instances were also compared to the results reported by Fischetti and Pisinger[13] where computer configuration is an Intel Xeon CPU X555 with 2.67 GHz. The comparative studies are given in the following subsections.

4.1 | Comparison of MIP and MIP_H on the test instances

Feasible and/or optimal solutions to the test instances obtained by MIP and MIP_H are reported in Table 3 where the run time limit is 24 hours for both models. Table 3 compares MIP and MIP_H models in terms of the total cable costs of the best solutions obtained within 24-hour of computer time (before and after the execution of repair procedure), the gap between the lower bound and the best solution, and the elapsed time until the best solution found. The results show that MIP_H reduces the solution time nearly 55% compared to MIP while providing 74% better gap. Additionally, average total costs obtained by MIP and MIP_H before and after the repair routine is applied are found very close to each other as seen in Table 3. Although MIP_H contains heuristically derived constraints, it is comparable to MIP model in terms of optimal cable costs while MIP_H is strictly superior to MIP in terms of run time. This result encourages us to apply MIP_H to larger size instances of real-life.

4.2 | Comparison of MIP and MIP_H on the test instances with two transmitters

Most of the optimization-based approaches proposed in the literature assign wind turbines to a single transmitter when there is more than one transmitter in the wind farm. Therefore, the multi-transmitter problem is decomposed into single-transmitter problems. Even MIP and MIP_H models are developed to deal with single-transmitter cable layout problem, in this subsection we analysed the performance of the models when there are two transmitters in the farm. For this purpose, MIP and MIP_H were extended according to the two-transmitter and test instances in Table 1 were changed by assuming (11, 10) is the location of the second transmitter in the layouts given by Figure 3. Both the models were executed for the instances Test1 to Test12 with two-transmitter allowing 10-hour computer time. Table 4 gives the results obtained from MIP and MIP_H and the results after the repair routine was applied. It is clear total

TABLE 2 Cable information[13]

Instance No.	Wind farm	Turbine type	TN	C (maximum cable number incident to transmitter)	Number of cable types	Capacity (maximum turbine number)	Cable price + install price, total price (Euros per metre)	Cable set name
Real1	Horns Rev 1 (Denmark)	Vestas 80-2-megawatt	80	10	3	7	370	CableSet1
						11	393	
						13	435	
Real2					2	7	441	CableSet2
						12	450	
Real3					2	10	440	CableSet3
						14	620	
Real4	Kentish Flats (United Kingdom)	Vestas 90-3-megawatt	30	∞	3	5	370	CableSet4
						8	393	
						9	435	
Real5					2	5	441	CableSet5
						8	450	
Real6					2	7	382	CableSet6
						15	630	
Real7					2	7	440	CableSet7
						10	620	
Real8	Ormonde (United Kingdom)	Senvion 5-megawatt	30	4	2	5	407	CableSet8
						10	607	
Real9					2	4	382	CableSet9
						9	630	
Real10	DanTysk (Denmark)	DanTysk Siemens 3.6-megawatt	80	10	3	4	370	CableSet10
						6	393	
						8	435	
Real11					2	6	440	CableSet11
						8	620	
Real12	Thanet (United Kingdom)	Thanet Vestas 90-3-megawatt	100	10	2	7	382	CableSet12
						15	630	
Real13					2	7	440	CableSet13
						10	620	

TABLE 3 Performance of the proposed models on the test instances

	MIP model						MIP_H model					
Instance No.	Total cable cost[a]	% Gap	Time[b] (s)	No. of execution of the repair procedure	Total cable cost[c]	Time[d] (s)	Total cable cost[a]	% Gap	Time[b] (s)	No. of execution of the repair procedure	Total cable cost[c]	Time[d] (s)
Test1	3 669 839	7.77	86 400.00	1	3 683 021	0.59	3 631 106	4.27	86 400.00	3	**3 655 421**	33.33
Test2	4 601 821	0.00	1.38	2	4 682 571	0.80	**4 610 449**	0.00	1.28	—	**4 610 449**	—
Test3	5 277 796	4.71	86 400.00	1	5 324 367	11.77	**5 235 162**	0.00	23 697.96	—	**5 235 162**	—
Test4	**3 488 040**	0.00	2425.53	—	**3 488 040**	—	3 539 856	0.00	9527.04	1	3 544 366	0.52
Test5	**5 169 642**	0.00	41 061.77	—	**5 169 642**	—	**5 169 642**	0.00	35 837.31	—	**5 169 642**	—
Test6	5 398 014	0.00	1417.88	3	**5 450 205**	1.87	5 398 014	0.00	60.90	3	5 524 842	1.87
Test7	**3 925 295**	3.34	86 400.00	—	**3 925 295**	—	**3 925 295**	0.00	25 556.64	—	**3 925 295**	—
Test8	5 613 334	0.00	68 871.39	2	**5 683 651**	0.61	5 660 806	0.00	813.37	3	5 853 049	0.44
Test9	6 134 711	5.06	86 400.00	1	**6 172 766**	0.62	6 053 770	0.00	24 301.87	8	6 653 475	3.37
Test10	**4 043 974**	4.19	86 400.00	—	**4 043 974**	—	**4 043 974**	0.00	25 041.12	—	**4 043 974**	—
Test11	**5 734 765**	0.84	86 400.00	—	**5 734 765**	—	5 802 822	0.00	3966.04	4	5 947 893	1.25
Test12	6 323 524	7.24	86 400.00	4	6 400 321	1.58	6 182 841	4.48	86 400.00	6	**6 315 049**	2.67
Average	**4 948 396.0**	**2.76**	**59 881.5**	**2**	**4 979 884.8**	**2.55**	**4 937 811.0**	**0.73**	**26 800.29**	**3**	**5 033 665.0**	**6.21**

[a]Total cable cost of the best solution obtained from the first solving of the related integer model.
[b]Computer time of the first solving of the related integer model.
[c]Total cable cost of the best solution without crossing cables.
[d]Total computer time spent for the executions of the repair procedure.

TABLE 4 Performance of the proposed models on the test instances with two transmitters

MIP model							MIP_H model					
Instance No.	Total cable cost[a]	% Gap	Time[b] (s)	No. of execution of the repair procedure	Total cable cost[c]	Time[d] (s)	Total cable cost[a]	% Gap	Time[b] (s)	No. of execution of the repair procedure	Total cable cost[c]	Time[d] (s)
Test1	3 541 637	6.05	36 000	—	3 541 637	—	**3 494 342**	3.84	36 000	—	**3 494 342**	—
Test2	**4 467 200**	0.00	5.08	—	**4 467 200**	—	**4 467 200**	0.00	4.23	—	**4 467 200**	—
Test3	5 331 274	11.09	36 000	—	5 331 274	—	**5 039 997**	5.32	36 000	—	**5 039 997**	—
Test4	**3 049 837**	0.00	59.92	—	**3 049 837**	—	**3 049 837**	0.00	140.8	—	**3 049 837**	—
Test5	**4 503 546**	0.00	36 000	—	**4 503 546**	—	4 695 810	9.30	36 000	—	4 695 810	—
Test6	4 911 641	6.64	36 000	1	4 943 287	1.28	**4 835 505**	4.58	36 000	—	**4 835 505**	—
Test7	3 891 668	7.56	36 000	1	3 906 625	1.62	**3 799 357**	3.41	36 000	—	**3 799 357**	—
Test8	5 647 462	14.14	36 000	1	5 717 536	0.64	**5 474 544**	8.66	36 000	—	**5 474 544**	—
Test9	6 026 518	14.63	36 000	1	**5 866 490**	0.68	5 872 272	10.71	36 000	1	5 896 563	1.8
Test10	3 924 168	8.30	36 000	—	**3 924 168**	—	4 133 390	12.78	36 000	—	4 133 390	—
Test11	5 688 210	7.67	36 000	—	5 688 210	—	**5 521 876**	5.23	36 000	—	**5 521 876**	—
Test12	6 249 275	14.53	36 000	—	6 249 275	—	**6 089 942**	10.81	36 000	—	**6 089 942**	—
Average	**4 769 370**	**7.55**	**30 005.42**	**1**	**4 765 757**	**1.06**	**4 706 173**	**6.22**	**30 012.09**	**1**	**4 708 197**	**1.80**

[a]Total cable cost of the best solution obtained from the first solving of the related integer model.
[b]Computer time of the first solving of the related integer model.
[c]Total cable cost of the best solution without crossing cables.
[d]Total computer time spent for the executions of the repair procedure.

TABLE 5 Performance of the proposed models on the real-world cases

MIP model							MIP_H model					
Instance No.	Total cable cost[a]	% Gap	Time[b] (s)	No. of execution of the repair procedure	Total cable cost[c]	Time[d] (s)	Total cable cost[a]	% Gap	Time[b] (s)	No. of execution of the repair procedure	Total cable cost[c]	Time[d] (s)
Real1	19 546 800	1.78	86 400	—	19 546 800	—	**19 465 350**	1.41	86 400	—	**19 465 350**	—
Real2	**22 616 830**	0.10	86 400	—	**22 616 830**	—	22 623 040	0.00	86 400	—	22 623 040	—
Real3	23 552 460	2.04	86 400	—	23 552 460	—	**23 457 760**	0.70	74 163	—	**23 457 760**	—
Real4	**8 555 171**	0.00	43.59	—	**8 555 171**	—	**8 555 171**	0.00	70.74	—	**8 555 171**	—
Real5	**10 056 670**	0.00	28.69	—	**10 056 670**	—	**10 056 670**	0.00	45.25	—	**10 056 670**	—
Real6	**8 604 209**	0.00	4.5	—	**8 604 209**	—	**8 604 209**	0.00	4.81	—	**8 604 209**	—
Real7	**10 173 930**	0.00	9.67	—	**10 173 930**	—	**10 173 930**	0.00	11.82	—	**10 173 930**	—
Real8	**8 054 845**	0.00	25 335.74	—	**8 054 845**	—	**8 054 845**	0.00	1050.03	—	**8 054 845**	—
Real9	8 375 956	2.62	86 400	—	8 375 956	—	**8 357 196**	0.00	9099.84	—	**8 357 196**	—
Real10	39 114 500	7.96	86 400	2	39 160 420	5.92	**38 976 050**	5.24	86 677	—	**38 976 050**	—
Real11	50 207 080	9.40	86 400	—	50 207 080	—	49 897 710	6.53	64 424	2	**50 048 860**	6.38
Real12	22 758 070	6.73	86 400	2	22 580 530	4.96	**22 338 290**	4.13	86 400	—	**22 338 290**	—
Real13	26 527 930	4.51	86 400	3	26 561 400	5.21	26 514 120	2.98	80 066	3	**26 541 180**	17.40
Average	**19 883 137.6**	**2.70**	**55 124.78**	**0.54**	**19 874 958.4**	**1.24**	**19 800 749.3**	**1.61**	**44 216.35**	**0.38**	**19 815 600.1**	**1.83**

[a]Total cable cost of the best solution obtained from the first solving of the related integer model.
[b]Computer time of the first solving of the related integer model.
[c]Total cable cost of the best solution without crossing cables.
[d]Total computer time spent for the executions of the repair procedure.

cable costs decreases compared to the costs of single-transmitter case since there exist more alternatives to install shorter cables between turbines and two transmitters. As seen from Table 4, all the instances, except Test2 and Test4, could not be solved optimally within 10-hour computer time limit. Thus, both the models exhibit similar run time in average. On the other hand, MIP_H generates more cost-effective layouts than MIP for seven instances while MIP outperforms MIP_H for three instances. The models result in the same solution to the remaining two instances. MIP_H decreases average cable costs of MIP by 1.2%. As an encouraging outcome, the experiments show that we can solve the two-transmitter cases in a single model without dividing problem into single transmitter cable layout problems.

4.3 | Comparison of MIP and MIP_H on the real-world cases

Results obtained by MIP and MIP_H models for 13 real-case instances are provided in Table 5 while Figures 4 and 5 give the cable layouts obtained by the respective models on the instances Real3 and Real11, respectively, as examples. As seen in Figure 4, MIP and MIP_H result in a different layout in which only 10-turbine capacitated cables are used for Real3. For Real11, the best solutions found by the models involve the two types of cables as represented by black lines (cable type with capacity of 6) and green lines (cable type with capacity of 8) in Figure 5. MIP_H model provides better results in the real-world instances in terms of total cost compared to MIP. There are six instances that MIP_H achieves better results than MIP for larger wind farms whereas both models generates the same solutions in five instances of small-sized wind farms. MIP generate a lower total cost than that of MIP_H only for two instances. In the real case applications, clearly, the repair procedure is required less compared to the test instances. The main reason for this situation is that turbines in the same row or column are assumed to be located in the same alignment in the grid design of test instances. Therefore, the possibility of having crossing cables increases. However, turbines in the real wind farms have somewhat divergent locations and crossing cables are observed less.

MIP_H reduces the average gap percentage nearly 40% compared to that of MIP, while MIP_H provides 0.3% cost saving according to the average cost generated by MIP. Even this saving percentage seems to be small, it should be noticed that the investment in wind farms, especially in offshore wind farms, is highly expensive, therefore even small savings in the total investment cost will be significant. Additionally, MIP_H provides nearly 19% faster execution time than the average execution time of MIP. Consequently, the heuristically enhanced integer model is superior to the original model in terms of both efficiency and effectiveness.

4.4 | Comparison of MIP_H and an existing study on the real-world cases

In this subsection, the performance of MIP_H is compared to the integer programming model and matheuristic approach proposed by Fischetti and Pisinger.[13] Since

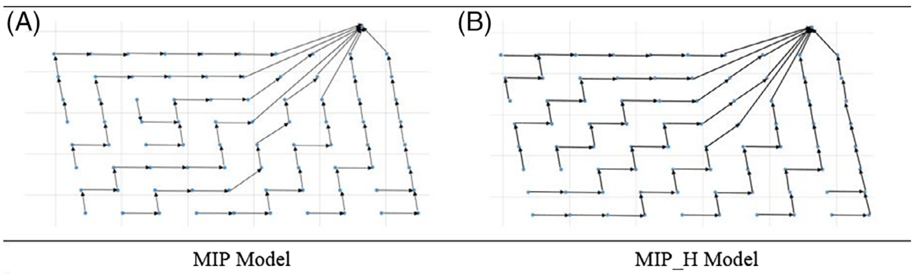

FIGURE 4 Cable layouts for instance Real3 [Colour figure can be viewed at wileyonlinelibrary.com]

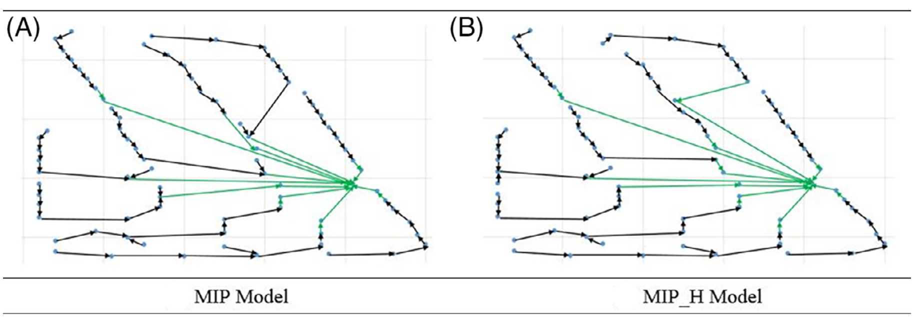

FIGURE 5 Cable layouts for instance Real11 [Colour figure can be viewed at wileyonlinelibrary.com]

MIP_H already has been found superior to MIP, results of the MIP model are not included in the present comparative study. Fischetti and Pisinger[13] developed a mixed integer programming model, let call MIP_FP, in which *Steiner* nodes are included to provide some flexibility to the cable layout. The authors used a data pre-processing to find the set of crossing arcs and avoided from crossing cables by introducing associated constraints for each pair of the arcs in the set. The matheuristic approach proposed by the authors for the same problem is a hybridization of MIP_FP and a set of heuristic rules. In the matheuristic, MIP_FP is used as a black-box and input data is changed to find a sequence of improved solutions. This process is repeated until a pre-defined computer time limit is achieved.

Table 6 and Table 7 give the comparative results obtained from MIP_FP and MIP_H within 10-hour and the results obtained from matheuristic and MIP_H within 24-hour, respectively. MIP_H and MIP_FP provide the same solutions for six small-sized instances out of totally 13 instances while MIP_H is able to find a

TABLE 6 Comparison of MIP_H with MIP_FP

	MIP_FP			MIP_H		
Instance No.	**Total cable cost**	**% Gap**	**Time**	**Total cable cost**	**% Gap**	**Time**
Real1	**19 437 283**	0.079	36 000	19 465 350	1.412	36 000
Real2	**22 611 989**	0.007	36 000	22 623 040	0.000	36 000
Real3	23 482 483	0.327	36 000	**23 457 760**	0.696	36 000
Real4	**8 555 171**	0.000	2.28	**8 555 171**	0.000	70.74
Real5	**10 056 670**	0.000	1.67	**10 056 670**	0.000	45.25
Real6	**8 604 209**	0.000	0.97	**8 604 209**	0.000	4.81
Real7	**10 173 932**	0.000	1.12	**10 173 930**	0.000	11.82
Real8	**8 054 845**	0.000	25.11	**8 054 845**	0.000	1050.03
Real9	**8 357 196**	0.000	117.08	**8 357 196**	0.000	9099.84
Real10	—	—	36 000	**38 976 050**	5.236	36 000
Real11	—	—	36 000	**50 048 860**	0.000	36 000
Real12	**22 336 017**	3.330	36 000	22 338 290	4.128	36 000
Real13	—	—	36 000	**26 541 180**	0.000	36 000

TABLE 7 Comparison of MIP_H with Matheuristic

	Matheuristic			MIP_H		
Instance No.	**Total cable cost**	**% Gap**	**Time**	**Total cable cost**	**% Gap**	**Time**
Real1	**19 436 700**	0.01	14 748.8	19 465 350	1.412	86 400
Real2	**22 611 989**	0.01	4621.3	22 623 040	0.000	86 400
Real3	23 482 483	0.17	86 400.3	**23 457 760**	0.696	74 163
Real4	**8 555 171**	0.00	43.0	**8 555 171**	0.000	70.74
Real5	**10 056 670**	0.00	28.3	**10 056 670**	0.000	45.25
Real6	**8 604 209**	0.00	23.1	**8 604 209**	0.000	4.81
Real7	**10 173 932**	0.00	24.4	**10 173 930**	0.000	11.82
Real8	**8 054 845**	0.00	247.8	**8 054 845**	0.000	1050.03
Real9	**8 357 196**	0.00	354.4	**8 357 196**	0.000	9099.84
Real10	38 977 594	5.10	86 400.4	**38 976 050**	5.236	86 677
Real11	50 379 247	7.94	86 400.5	**50 048 860**	0.000	64 424
Real12	**22 337 936**	3.49	86 400.6	22 338 290	4.128	86 400
Real13	26 637 602	2.57	86 400.5	**26 541 180**	0.000	80 082

feasible solution for three instances which cannot be solved by MIP_FP. On the other hand, MIP_H generates lower cost solutions for four instances compared to matheuristic within 24-hour while both the methods solve small instances optimally. In average, MIP_H provides about 0.16% cost saving and reduces the gap percentage about 6% compared to matheuristic. Computer time required by MIP_H is nearly 21% more than that of matheuristic in average. However, it should be rementioned that investment cost in an offshore wind farm is very high, especially, as the number of turbines increases and therefore, solution time is not very important if eventually a better solution would be obtained.

5 | CONCLUSION

In this study, one of the main problems in the design of wind farms, namely cable layout problem, is addressed. The problem entails deciding of cable connections between each pair of turbines and one or several transmitters in a wind farm to minimize the sum of the cable costs where cross-cables are not allowed. This problem is especially important for offshore wind farms since the cable costs may constitute up to 20% of the total investment cost. Cable layout problem is an NP-hard problem because any feasible solution to the problem must be at least a capacitated spanning tree. Two integer programming models, MIP and MIP_H, are presented for solving of the problem. While MIP model guarantees having an exact optimum solution if it is possible depending on the size or input data of the given instance, MIP_H in which several heuristically derived constraints are involved provides good feasible solutions. Furthermore, a new repair algorithm is presented to eliminate cross-cables in the layouts generated by the proposed models. An experimental study on a suit set of instances of the cable layout problem reveals that even MIP_H cannot guarantee the optimality, it is capable to find optimal solutions for small- or moderate-sized instances in terms of total turbine numbers. Moreover, MIP_H is superior to MIP in solving the instances of real-world large wind farms within a reasonable amount of computer time. The computational time requirement is reduced nearly 19% using MIP_H according to the time requirement of MIP on these instances. MIP_H is also compared with an integer programming model and a heuristic approach which are proposed in the related literature for real-world wind farms. It is observed that all the methods can solve the cable layout problem optimally for small wind farms. On the other hand, MIP_H outperforms the results reported in the literature for the large-sized instances where the turbines are scattered in the site of wind farm. Additionally, MIP and MIP_H models are extended to apply two-transmitter wind farms and it is observed that both the models can solve two-transmitter test cases while MIP_H produces more cost-effective layouts within shorter computer time. Consequently, MIP_H model can be a good alternative in the design of cable layouts of large wind farms to reduce total cable costs.

As a future study, we are planning to extend and modify MIP_H as including the different complexities in the design of cable layouts such as power losses, heterogonous turbine types, and more than two transmitters. Another challenging problem in the installation of wind farms is to design turbine locations and cable layout simultaneously to minimize both total wake effects and total cable costs. We are also intending to develop integrated heuristic approaches based on optimization to deal with this multi-objective problem.

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